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# Modified Tables for the Design of Optimum Diplexers

R. G. VELTROP

R. B. WILDS



SYLVANIA ELECTRONIC SYSTEMS
Government Systems Management
for GENERAL TELEPHONE & ELECTRONICS

GENERAL SYSTEM

**ELECTRONIC DEFENSE LABORATORIES**

MOUNTAIN VIEW CALIFORNIA

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R. G. Veltrop
R. B. Wilds

Approved for publication . . . . R. E. Booth
Manager
Microwave Department

R. D. Kelch
Head
Microwave Engineering Section

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SYLVANIA ELECTRIC PRODUCTS INC.

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## 2. INTRODUCTION.

Diplexers are widely used for splitting a broad frequency band into two smaller bands of arbitrary width using selective filters. The design method described herein calls for the use of singly terminated low-pass and high-pass filters. As pointed out by Matthaei[1], the use of singly terminated filters circumvents the problems of modifying the diplexed ends of filters designed for resistor terminations at both ends. The compensation or annulling networks used with doubly terminated filters are not required. Singly terminated low-pass and high-pass filters designed from the Butterworth element values and denormalized to the same cut-off frequency are complementary. This is not the case however, for Chebyshev filters. Therefore, tables of modified element values for the design of diplexers with quasi-complementary Chebyshev filters have been derived. The validity of the modified values has been verified mathematically and experimentally for a diplexer consisting of 10-element, 0.25-db ripple Chebyshev low- and high-pass filters.

Although this report is concerned only with a single diplexer, the method could be extended to yield a number of contiguous channels to form a very broad band multiplexer.

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## 3. QUASI-COMPLEMENTARY CHEBYSHEV DIPLEXERS.

Perfect diplexing can be theoretically obtained with filter element values corresponding to the tables for singly terminated Butterworth filters or maximally flat filters. A low-pass/high-pass diplexer designed using these table values yields complementary impedance or admittance functions at the common junction at all frequencies including the region of crossover. For example, the normalized element values in farads and henrys for a three-element maximally flat, singly terminated, low-pass filter (r = 0) are given by Weinberg[2] as

| $C_1$, $L_1'$ | $L_2$, $C_2'$ | $C_3$, $L_3'$ |
|---|---|---|
| 0.500 | 1.333 | 1.500 |

The corresponding high-pass filter can be obtained by replacing each inductance with a capacitance equal to $1/L$ farads, and replacing each capacitance with an inductance equal to $1/C$ henrys. Using these values, a constant conductance diplexer (Figure 1a) or a constant resistance diplexer (Figure 1b) can be formed.

The diplexer of Figure 1a has an input admittance at the common junction of $1 + j0$ at all frequencies, and the dual circuit of Figure 1b has an input impedance at the common junction of $1 + j0$ at all frequencies. Each circuit has the same insertion loss function with the 3-db crossover point at $\omega = 1$ radian.

Frequently, it is desirable to form diplexers using Chebyshev or equal-ripple element values to take advantage of the greater selectivity that can be obtained. Also, the element values using Chebyshev tables of moderate ripple values can often be realized more easily with practical construction techniques. However, in the design of diplexers, the Chebyshev table values for r = 0 do not produce perfectly complementary low-pass/high-pass filter pairs as do the table values for maximally flat diplexers.

A shunt-connected diplexer is shown in Figure 1a. At the crossover frequency, the power should be split equally between the two outputs and there should be no reflected power. To accomplish this, it is obvious that the normalized input conductance of each filter must be 0.5 at the common junction and the individual susceptance values of both filters must add to zero. An example is given to illustrate what does happen with a diplexer designed from unmodified Chebyshev tables. The admittance characteristics of a filter pair designed from

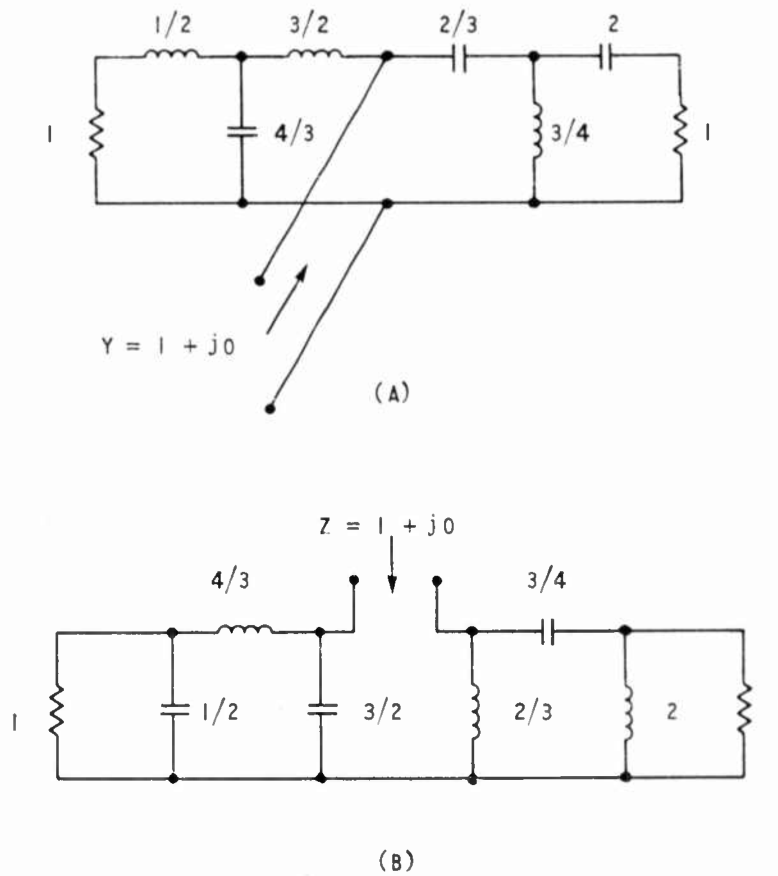


Figure 1

Maximally Flat Diplexer

3. -- Continued.

the $r = 0$ tables, 0.25-db ripple, and $n = 10$ reactive elements were computed and are shown in Figure 2. The conductance of each filter remains nominally at 1.0 throughout the pass band up to the crossover frequency ($\omega = 1$ radian) and then drops virtually to zero in its stop band. The sum of the two conductance values at the common junction remains nominally at 1.0 throughout the entire frequency range except in the vicinity of crossover. At $\omega = 1$ radian, the net conductance reaches a maximum of about 2.0. Both filters have reasonably smooth susceptance characteristics which rise to a peak at the frequency where filter conductance is 0.5. The net susceptance at the common junction does add to zero at $\omega = 1$, but there is a small amount of residual susceptance over the remainder of the frequency range with maxima just on each side of crossover. The theoretical performance of this diplexer is not too bad. The input VSWR remains below 1.2 over most of the band-pass regions and rises to about 2 to 1 at crossover. This indicates a crossover loss of about 3.5 db to each channel.

The general shape of the admittance characteristics is typical of Chebyshev filter pairs for any ripple value and any number of reactive elements. Of course, the steepness of the conductance characteristic and the peak value of the susceptance characteristic do change with ripple value and number of elements. It is also interesting to note that there is very little ripple in either the conductance or susceptance curves, certainly much less than would be present in a doubly terminated filter designed from $r = 1$ tables.

Closer examination of the admittance characteristics shows that nearly perfect diplexer performance can be obtained by modifying the element values of the low-pass and high-pass filter to place the 0.5 conductance points of both filters at the crossover frequency. This amounts to shifting the cut-off frequency of the low-pass filter down and the cut-off frequency of the high-pass filter up by an appropriate factor. It becomes apparent that, when this modification is performed, the sum of the input conductances at the common junction remains nominally at 1.0 throughout the crossover region. Also, the susceptance curves are shifted to provide fairly effective cancellation over the entire frequency range.

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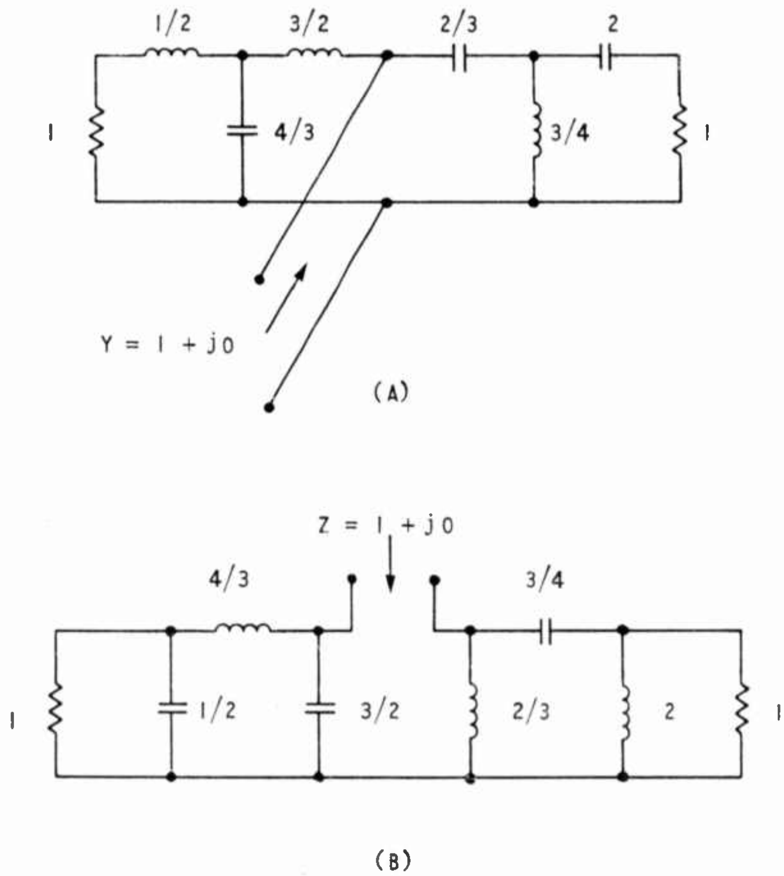


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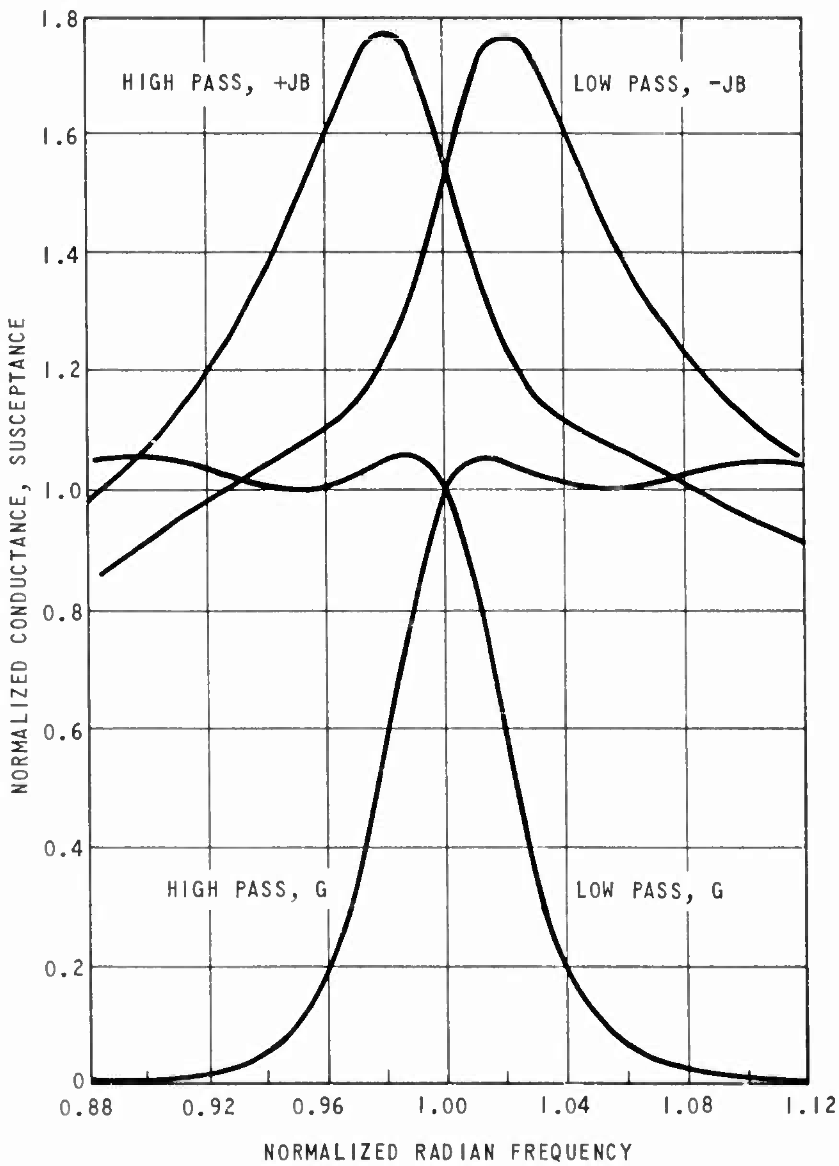


Figure 2

Admittance Characteristics of a Diplexer Designed from Unmodified Chebyshev Tables; r = 0, 0.25-db Ripple, n = 10

## 3.1 Modified Chebyshev Tables for Diplexer Design.

Since the cut-off rate of a filter is a function of both ripple value and number of reactive elements, it follows that a separate modification factor must be applied for each ripple value and n value. Matthaei[1] has developed the general expression for the normalized input conductance of singly terminated, low-pass Chebyshev filters:

$$\frac{\mathrm{Re}\ Y}{G_o} = (1+\epsilon)\left[1+\epsilon\ \cosh^2\left(n \cosh^{-1}\frac{\omega'}{\omega'_1}\right)\right]^{-1} \qquad (1)$$

where

$$\epsilon = \left[\left(\mathrm{antilog}\ \frac{A_m}{10}\right) - 1\right] \qquad (2)$$

$A_m$ is the equal ripple value in db, n is the number of reactive elements, $\omega'_1$ is the radian cut-off frequency which is equal to 1 in the normalized case, and $\omega'$ is an arbitrary radian frequency greater than 1. For n odd, the factor $(1+\epsilon)$ is set equal to 1.

To determine the modification factor, the normalized input conductance is set equal to 0.5 and the expression is rearranged to yield:

$$\omega'_{3\ db} = \cosh\left(\frac{1}{n}\ \cosh^{-1}\sqrt{\frac{1+2\epsilon}{\epsilon}}\right),\ n\ \text{even}, \qquad (3)$$

and

$$\omega'_{3\ db} = \cosh\left(\frac{1}{n}\ \cosh^{-1}\sqrt{\frac{1}{\epsilon}}\right),\ \ n\ \text{odd}. \qquad (4)$$

For the particular case of n = 10 elements and 0.25-db ripple ($\epsilon = 0.0593$), $\omega'_{3\ db} = 1.023$. To obtain the modified low-pass table values, each inductance and capacitance is multiplied by 1.023. This, in effect, lowers the cut-off frequency of the filter to $\frac{1}{1.023}$ of its original value and places the 0.5 normalized conductance value at the crossover frequency of $\omega = 1$ radian.

3.1 -- Continued.

To obtain the modified element values for the quasi-complementary high-pass filter, each modified inductance is replaced with a capacitance equal to 1/L farads, and each modified capacitance is replaced with an inductance equal to 1/C henrys. The effect of inverting the modified low-pass values is to raise the cut-off frequency of the high-pass filter to 1.023 times its original value and to place its 0.5 normalized conductance value at the crossover frequency of $\omega = 1$ radian. Since the low-pass to high-pass transformation procedure is a simple inversion process, tables of modified Chebyshev element values are given for the low-pass prototype filters only. Tables 1 through 4 present the modified element values for 0.1-, 0.25-, 0.5-, and 1.0-db ripple, each for three to ten reactive elements.

## 3.2 Selectivity Characteristics of Quasi-Complementary Filter Pairs.

If the sum of the conductance at the common junction is equal to 1.0 at all frequencies and the net susceptance is zero, then the fractional power transferred to the output port of either filter is equal to its respective normalized input conductance. Therefore, with the aid of Equations (1), (3), and (4), expressions for the stop band insertion loss may be written

$$IL = 10 \log_{10} \frac{1}{(1+\epsilon)} \left[ 1 + \epsilon \cosh^2 \left( n \cosh^{-1} \left[ \omega'' \cosh \frac{1}{n} \cosh^{-1} \sqrt{\frac{1+2\epsilon}{\epsilon}} \right] \right) \right],$$

n even, (5)

$$IL = 10 \log_{10} \left[ 1 + \epsilon \cosh^2 \left( n \cosh^{-1} \left[ \omega'' \cosh \frac{1}{n} \cosh^{-1} \sqrt{\frac{1}{\epsilon}} \right] \right) \right],$$

n odd, (6)

where $\omega''$ is an arbitrary radian frequency greater than 1, relative to a radian frequency of 1 at the 3-db crossover point. The filter pair possesses geometric symmetry. Therefore, the stop-band insertion loss of the high-pass filter may also be obtained from Equations (5) and (6) by inverting the radian frequency $\omega''$, since for the high-pass filter the stop band will be at radian frequencies less than unity.

TABLE 1

MODIFIED ELEMENT VALUES IN FARADS, HENRYS AND OHMS FOR A NORMALIZED CHEBYSHEV FILTER RIPPLE OF 0.1 DB, SINGLY TERMINATED FOR IDEAL DIPLEXERS

| Value of n | $C_1/L_1'$ | $L_2/C_2'$ | $C_3/L_3'$ | $L_4/C_4'$ | $C_5/L_5'$ | $L_6/C_6'$ | $C_7/L_7'$ | $L_8/C_8'$ | $C_9/L_9'$ | $L_{10}/C_{10}'$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | .7162 | 1.5085 | 1.5128 | | | | | | | |
| 4 | .6747 | 1.4597 | 1.7739 | 1.5156 | | | | | | |
| 5 | .6508 | 1.4174 | 1.7661 | 1.8072 | 1.5614 | | | | | |
| 6 | .6392 | 1.3954 | 1.7508 | 1.8328 | 1.8862 | 1.5358 | | | | |
| 7 | .6308 | 1.3786 | 1.734 | 1.827 | 1.9210 | 1.8578 | 1.5748 | | | |
| 8 | .6264 | 1.3697 | 1.7247 | 1.8218 | 1.9271 | 1.9027 | 1.9125 | 1.5437 | | |
| 9 | .6223 | 1.3612 | 1.7152 | 1.8137 | 1.923 | 1.9095 | 1.9585 | 1.8729 | 1.5804 | |
| 10 | .6202 | 1.3566 | 1.7099 | 1.8093 | 1.9205 | 1.9112 | 1.9711 | 1.9227 | 1.9211 | 1.5468 |

Load end

Diplexed end

TABLE 2

MODIFIED ELEMENT VALUES IN FARADS, HENRYS, AND OHMS FOR A NORMALIZED CHEBYSHEV FILTER RIPPLE OF 0.25 DB, SINGLY TERMINATED FOR IDEAL DIPLEXERS

| Value of n | $C_1/L_1'$ | $L_2/C_2'$ | $C_3/L_3'$ | $L_4/C_4'$ | $C_5/L_5'$ | $L_6/C_6'$ | $C_7/L_7'$ | $L_8/C_8'$ | $C_9/L_9'$ | $L_{10}/C_{10}'$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | .8163 | 1.5280 | 1.5342 | | | | | | | |
| 4 | .7910 | 1.5169 | 1.8341 | 1.4925 | | | | | | |
| 5 | .7524 | 1.4738 | 1.8225 | 1.7822 | 1.5763 | | | | | |
| 6 | .7639 | 1.4768 | 1.8392 | 1.8256 | 1.9280 | 1.5114 | | | | |
| 7 | .7559 | 1.4629 | 1.8261 | 1.8235 | 1.9663 | 1.8284 | 1.6013 | | | |
| 8 | .7537 | 1.4591 | 1.8235 | 1.8249 | 1.9790 | 1.8780 | 1.9486 | 1.5176 | | |
| 9 | .7500 | 1.4522 | 1.8156 | 1.8191 | 1.9769 | 1.8862 | 1.9965 | 1.8412 | 1.6071 | |
| 10 | .7491 | 1.4508 | 1.8142 | 1.8186 | 1.9785 | 1.8917 | 2.0130 | 1.8932 | 1.9561 | 1.5207 |

Load end　　　　Diplexed end

TABLE 3

MODIFIED ELEMENT VALUES IN FARADS, HENRYS, AND OHMS FOR A NORMALIZED CHEBYSHEV FILTER RIPPLE OF 0.50 DB, SINGLY TERMINATED FOR IDEAL DIPLEXERS

| Value of n | $C_1'/L_1'$ | $L_2'/C_2'$ | $C_3'/L_3'$ | $L_4'/C_4'$ | $C_5'/L_5'$ | $L_6'/C_6'$ | $C_7'/L_7'$ | $L_8'/C_8'$ | $C_9'/L_9'$ | $L_{10}'/C_{10}'$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | .9316 | 1.5176 | 1.5718 | | | | | | | |
| 4 | .9241 | 1.5398 | 1.9119 | 1.4537 | | | | | | |
| 5 | .9034 | 1.5136 | 1.9216 | 1.7397 | 1.6298 | | | | | |
| 6 | .9032 | 1.5162 | 1.9361 | 1.7903 | 1.9910 | 1.470 | | | | |
| 7 | .8946 | 1.5034 | 1.9236 | 1.7893 | 2.0304 | 1.7772 | 1.6462 | | | |
| 8 | .8954 | 1.5052 | 1.9243 | 1.7968 | 2.0505 | 1.8307 | 2.0086 | 1.4757 | | |
| 9 | .8911 | 1.4982 | 1.9199 | 1.7911 | 2.0482 | 1.8383 | 2.0571 | 1.7891 | 1.6533 | |
| 10 | .8919 | 1.4997 | 1.9224 | 1.7943 | 2.0538 | 1.8472 | 2.0777 | 1.8425 | 2.0151 | 1.4784 |

Load end

Diplexed end

TABLE 4

MODIFIED ELEMENT VALUES IN FARADS, HENRYS, AND OHMS FOR A NORMALIZED CHEBYSHEV FILTER RIPPLE OF 1.0 DB, SINGLY TERMINATED FOR IDEAL DIPLEXERS

| Value of n | $C_1'/L_1'$ | $L_2'/C_2'$ | $C_3'/L_3'$ | $L_4'/C_4'$ | $C_5'/L_5'$ | $L_6'/C_6'$ | $C_7'/L_7'$ | $L_8'/C_8'$ | $C_9'/L_9'$ | $L_{10}'/C_{10}'$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 1.1078 | 1.4597 | 1.6520 | | | | | | | |
| 4 | 1.1274 | 1.5174 | 2.0510 | 1.3768 | | | | | | |
| 5 | 1.1035 | 1.4929 | 2.0612 | 1.6446 | 1.7215 | | | | | |
| 6 | 1.1126 | 1.5080 | 2.0935 | 1.7048 | 2.1163 | 1.3898 | | | | |
| 7 | 1.1018 | 1.4947 | 2.0789 | 1.7024 | 2.1557 | 1.6773 | 1.7412 | | | |
| 8 | 1.1072 | 1.5022 | 2.0915 | 1.7160 | 2.1848 | 1.7334 | 2.1307 | 1.3943 | | |
| 9 | 1.1012 | 1.4944 | 2.0815 | 1.7094 | 2.1807 | 1.7392 | 2.1798 | 1.6881 | 1.7497 | |
| 10 | 1.1047 | 1.4992 | 2.0889 | 1.7161 | 2.1914 | 1.7510 | 2.2060 | 1.7418 | 2.1360 | 1.3964 |

Load end

Diplexed end

## 4. CALCULATED PERFORMANCE OF A DIPLEXER USING MODIFIED ELEMENT VALUES.

To check the validity of the modified values, the same diplexer described in Section 2 with 0.25-db ripple and n = 10 was designed from the modified tables. Figure 3 shows the normalized element values for the diplexer.

It is seen that the first element in the low-pass filter is a series inductance so that the input susceptance of the filter in its stop band will be small. Similar reasoning determines a series capacitor for the first element in the high-pass filter. The input admittance of both filters was calculated from .25 $\omega_c$ to 3 $\omega_c$ with an IBM 1620 computer. From these admittance values, the performance of the diplexer was computed as to input admittance and power split as functions of frequency. Figure 4 displays the input conductance and susceptance for the filter pair in the crossover region. The normalized total input conductance is very near unity at all the calculated frequencies. Virtual cancellation of the susceptances at all the calculated frequencies was also determined. Power division (Figure 5) as a function of frequency shows that a 3-db crossover is theoretically possible.

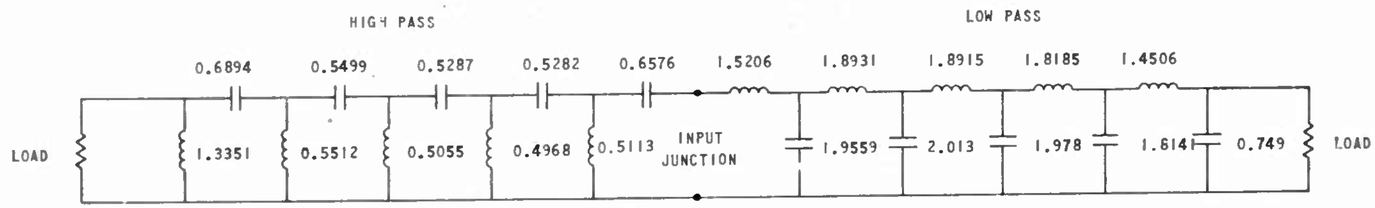


Figure 3

Normalized Values in Farads, Henrys, and Ohms for an Optimum Diplexer with 10-Element, 0.25-db Ripple Filters

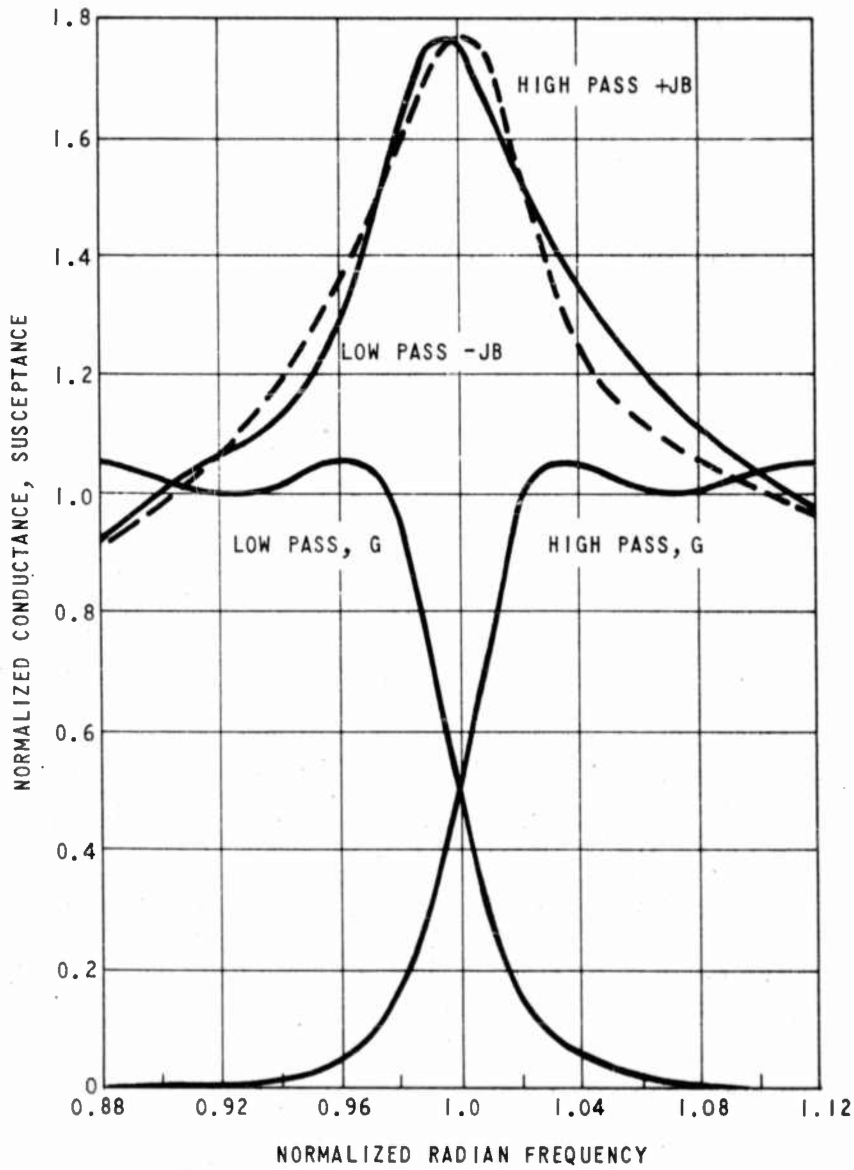


Figure 4

Admittance Characteristics of a Diplexer Designed from Modified Chebyshev Tables; r = 0, 0.25-db Ripple, n = 10

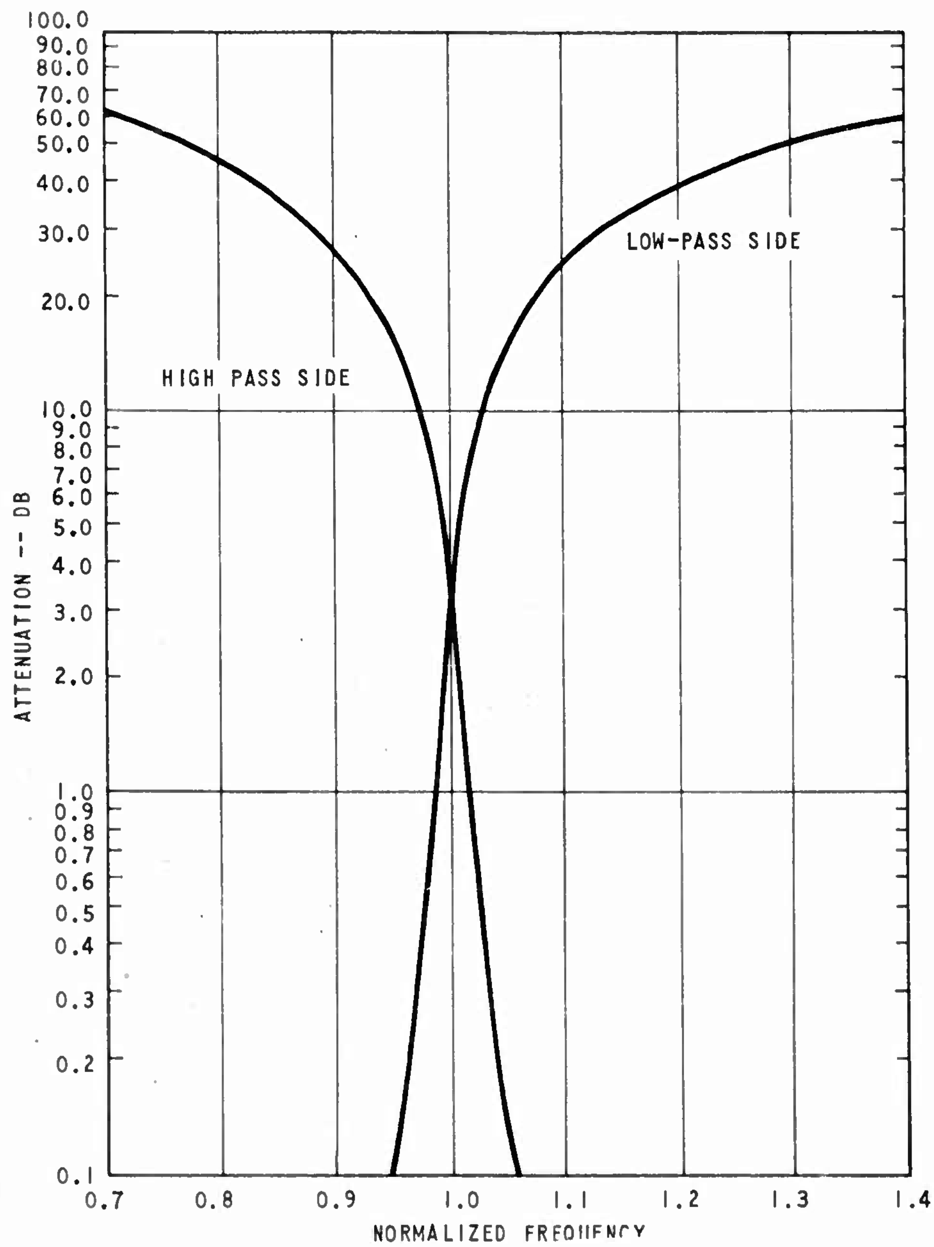


Figure 5

Insertion Loss Properties of an Optimum Diplexer
with 10-Element, 0.25-db Ripple Filters

## 5. MEASURED PERFORMANCE.

A diplexer with a 500-Mc crossover was designed from the normalized element values given in Figure 3. Denormalization as to impedance level and operating frequency is accomplished by multiplying every resistance in the prototype by R (the impedance level of the network), every inductance by $\frac{R}{2\pi f_c}$, and every capacitance by $\frac{1}{2\pi f_c R}$. The desired crossover frequency of the diplexer is $f_c$. Measured performance was not as ideal as that predicted mathematically either as to input VSWR or insertion loss. The VSWR characteristic shown in Figure 6 exhibits rather prominent variations around the crossover frequency, probably due to the steep slopes of the susceptances of both filters in this region and the inability to achieve complete cancellation. Only slight departures in realization from the correct values in any of the 20 elements making up the diplexer will degrade the performance from theoretical. A 3-db crossover was not achieved (Figure 7). However, 4-db crossover values were readily obtained. With fewer elements, performance closer to theoretical is undoubtedly obtainable. As the number of elements is increased, the crossover characteristics of the filters become steeper, making realization for ideal performance more difficult. The same thing is true for increasing the ripple value of the filters.

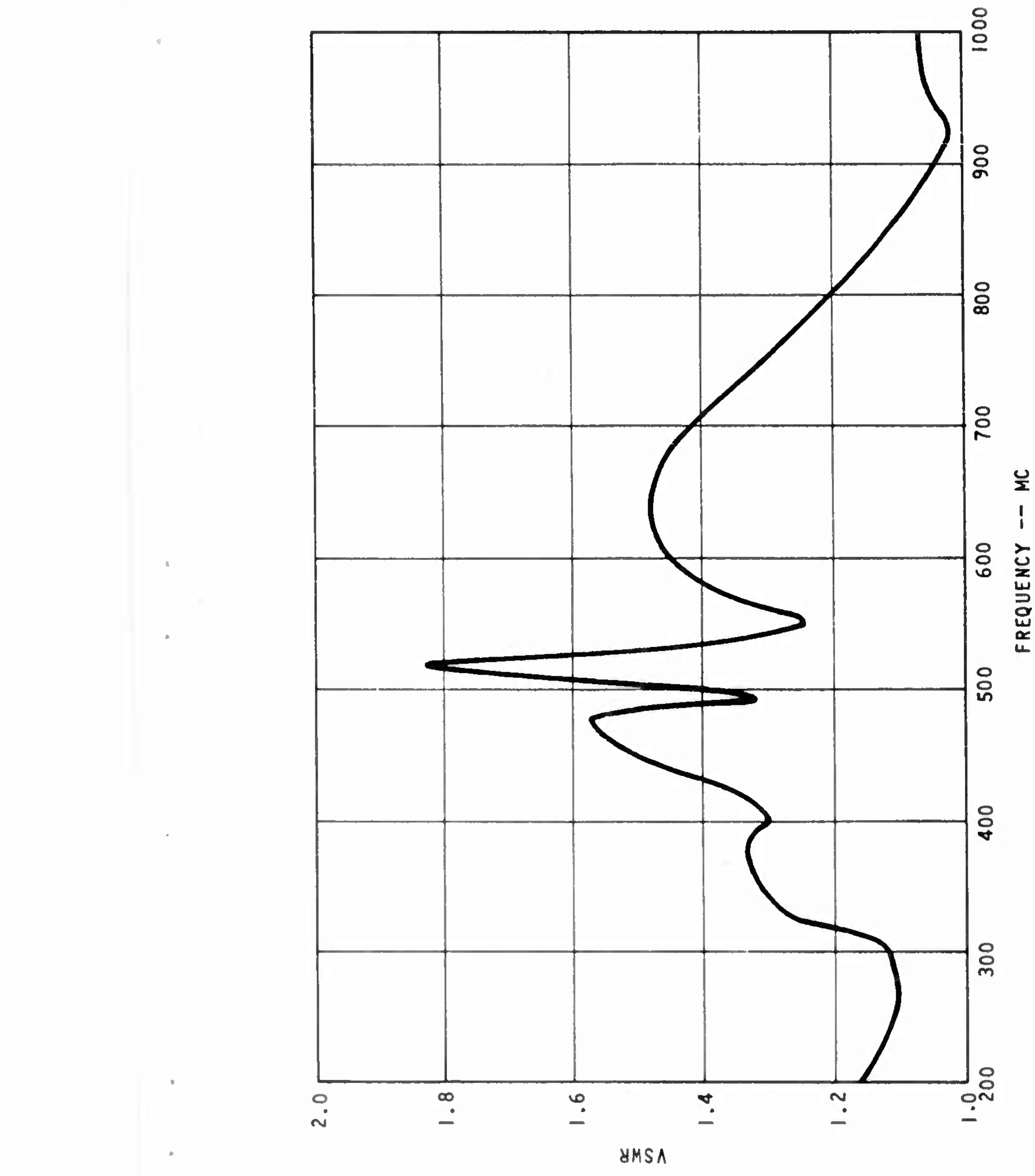


Figure 6

Input VSWR of 500-Mc Crossover Diplexer

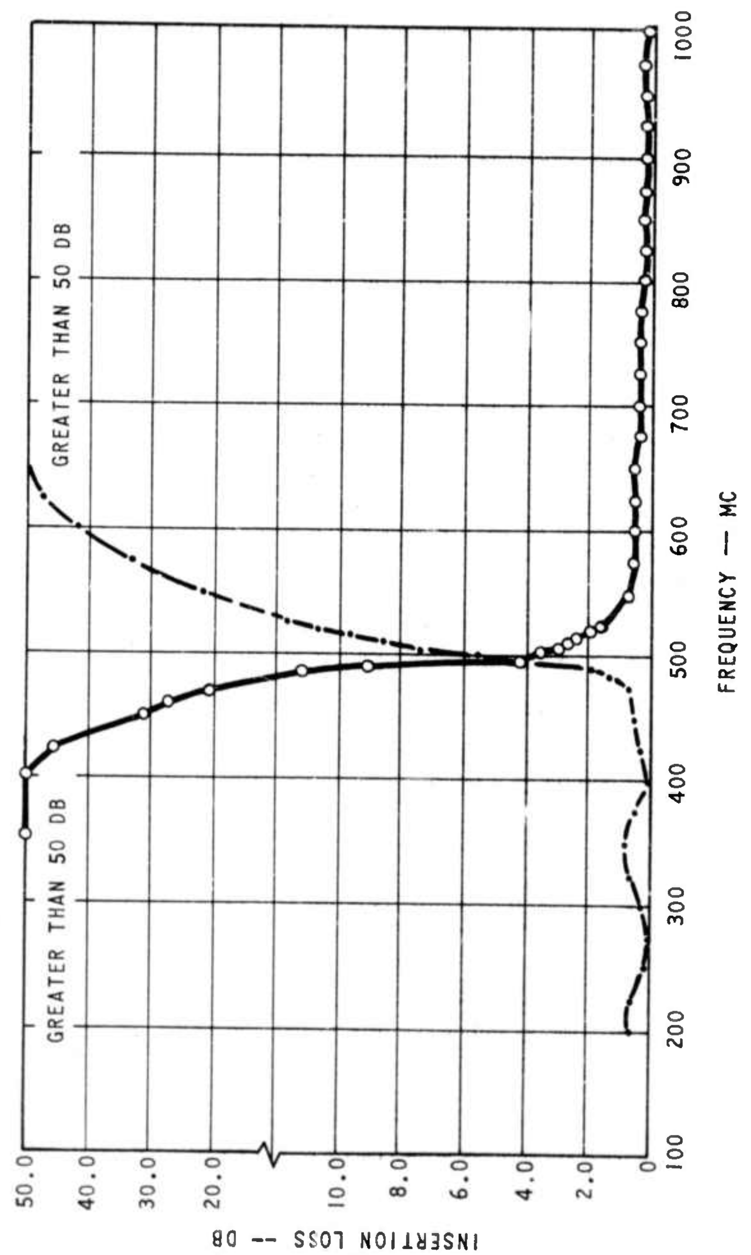


Figure 7

Insertion Loss of 500-Mc Crossover Diplexer

## 6. REALIZATION.

Coaxial split-block construction (Figure 8) was used for the physical realization of the 500-Mc diplexer. The inductances for both low- and high-pass filters were made with 10-mil diameter silver wire wound on a 4-40 nylon threaded rod. The series capacitors for the high-pass filter were small discs of double copper clad teflon fiber glass laminate (0.020" dielectric thickness). These small series capacitors were soldered between short segments of the center conductor using indium solder. The nylon rod was threaded into the short line segments as supports for the shunt inductances. The shunt capacitors in the low-pass structure were of the widely used coaxial type with teflon dielectric. The centers of these capacitors were threaded for the nylon rod which formed the support for the series inductances.

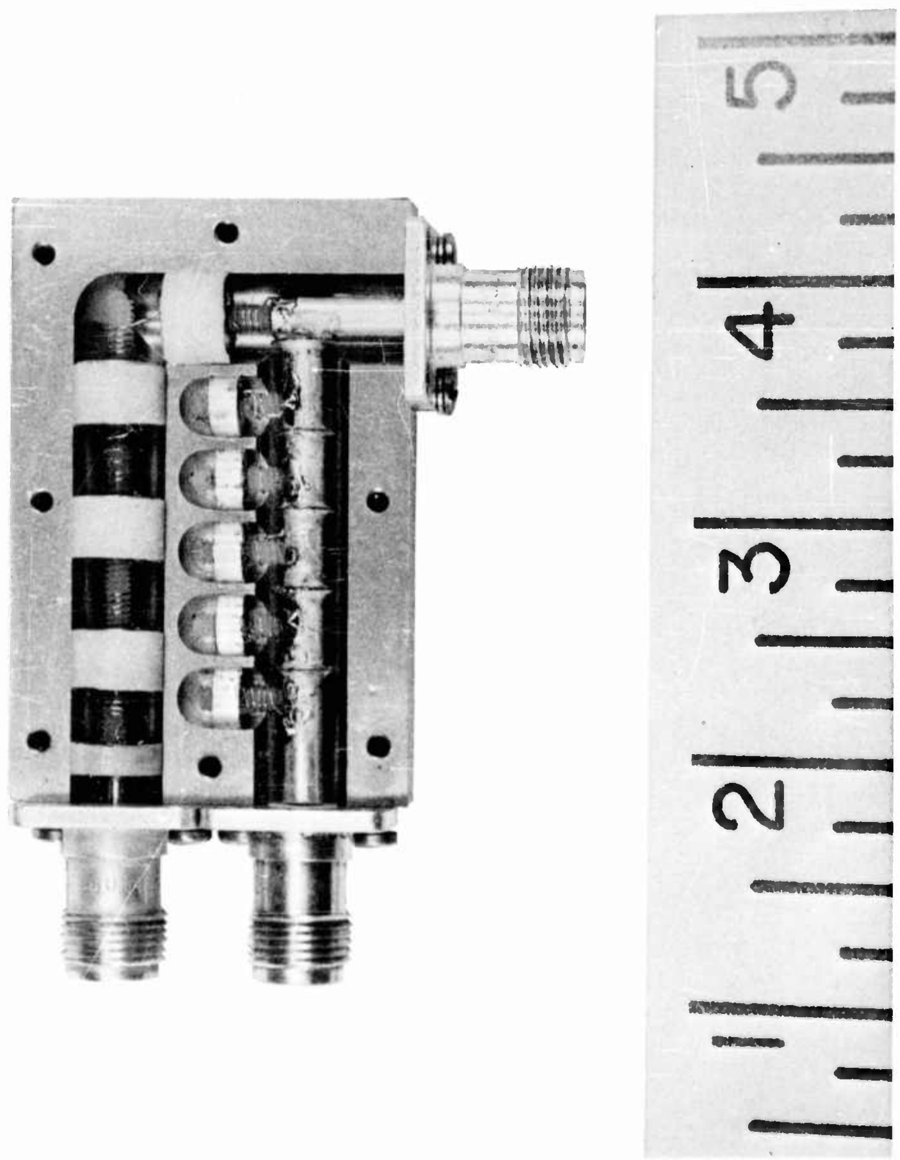


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Figure 8

500-Mc Crossover Diplexer

## 7. CONCLUSIONS.

The modified tables presented here should be useful in the design of diplexers where the sharp skirt selectivity of Chebyshev filters is required. It has been the authors' experience that the practical realization of diplexer circuits is facilitated by a design which is optimum rather than approximate. The calculated and experimental results given here are for only a single diplexer and one type of configuration. The design procedure, however, is general and can be extended to yield circuits consisting of a number of channels. There is no known restriction on the type of physical configuration. Matched input diplexers should find wide usage in band splitting, harmonic suppression, frequency multipliers, and solid-state circuits.

## 8. ACKNOWLEDGEMENT.

The authors acknowledge the assistance and cooperation of R. Dunphy, who was responsible for the realization and evaluation of the 500-Mc crossover diplexer.

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